



TTCS

TTCS Critical Design Review



Tracker Thermal Control System

AMS-CDR Meeting

Milano, March 10, 2004

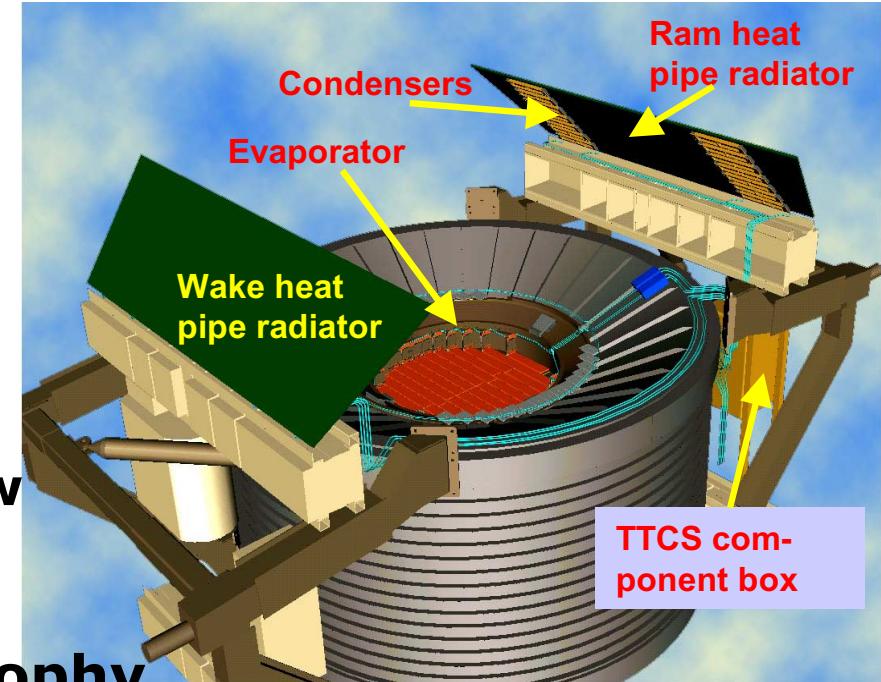
AMS Tracker Thermal Control System (TTCS)

Johannes van Es (NLR), Michel Brouwer (NLR), Bart Verlaat (NIKHEF),
Aswin Pauw (NLR), Gerrit van Donk (NLR)
& soon in co-operation with Sun Yat Sen University



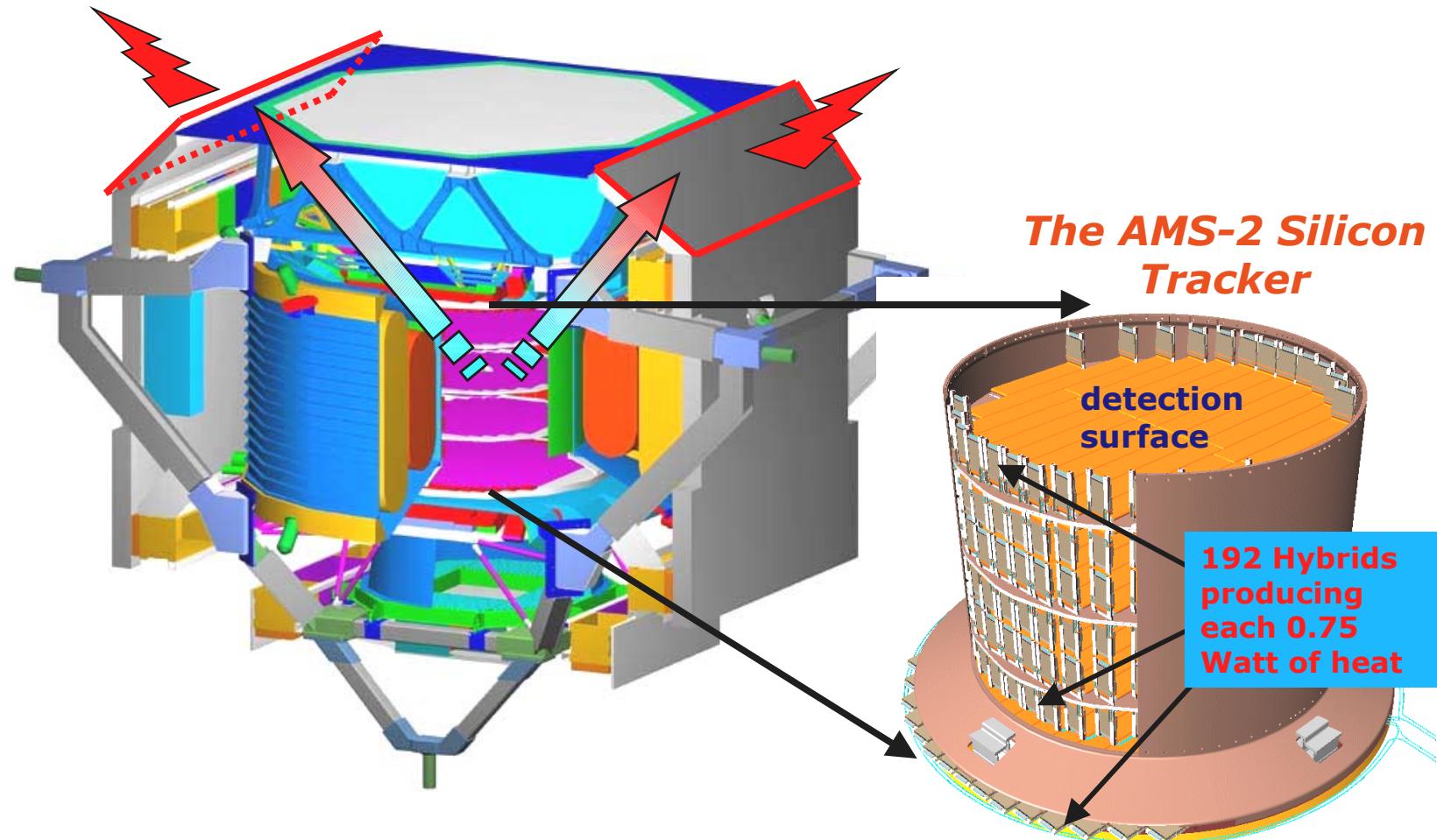
Contents

- TTCS introduction
- Requirements
- System Overview
 - Loop lay-out
 - Loop Components Overview
 - Loop Components
- Model & Verification Philosophy
- Condenser and freezing
- Survival Heaters



TTCS Introduction

Radiators for the Tracker ($2 \times 1.25 \text{ m}^2$)



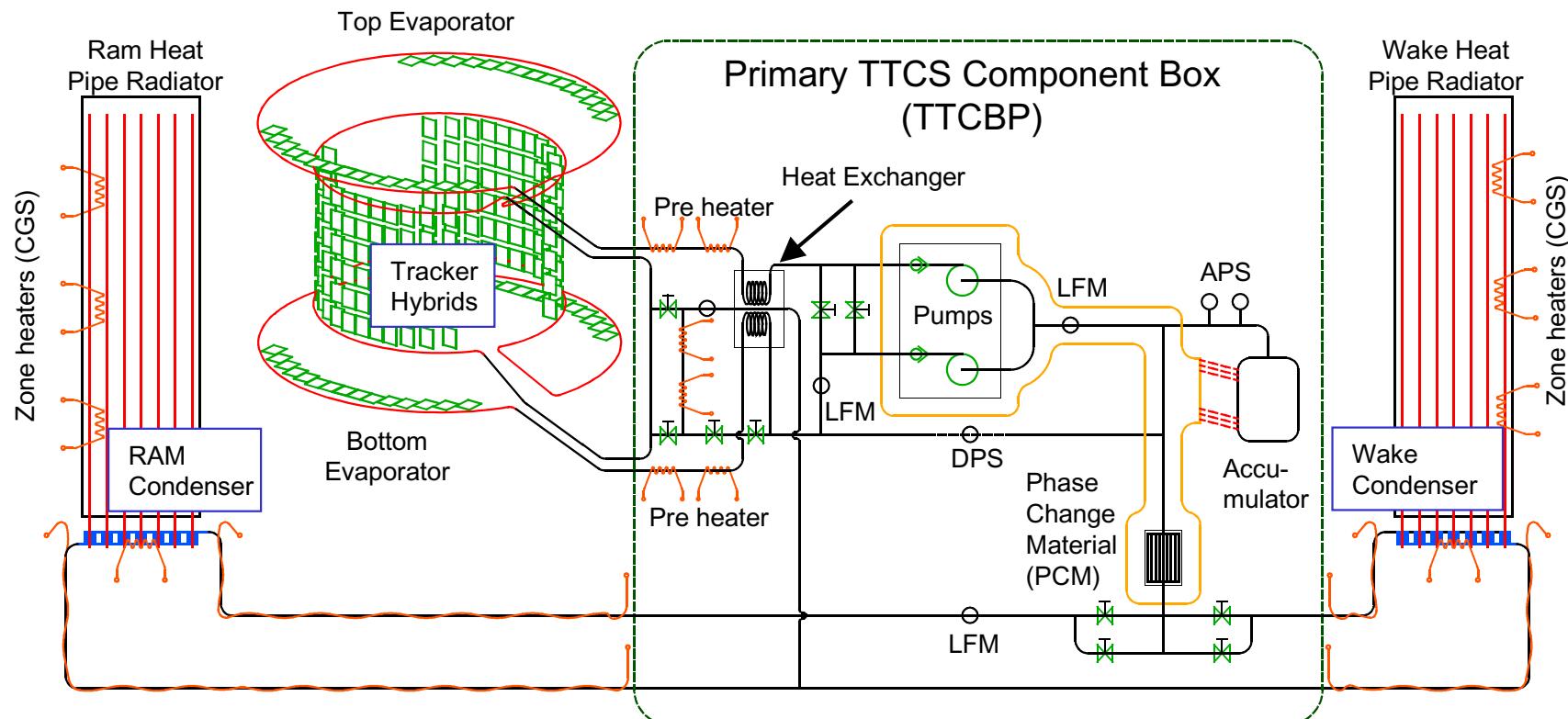
TTCS Introduction

- Two redundant carbon dioxide two-phase loops
(both capable to fulfil the AMS-Tracker req's)
 - Primary loop (with valve controls, experiment by-pass, LFM's)
 - Secondary loop (current status, no valves, no experiment by-pass, no LFM's)

TTCS Critical Design Review

Tracker Thermal Control System

Primary TTCS (TTCSP)



2-Way Valve (VLV)
Centrifugal pump (PMP)
with integrated check
valve



Electrical Heater (HTR)



Sensors:
LFM = Liquid Flow Meter,
DPS = Differential Pressure Sensor
APS = Absolute Pressure Sensor
VQS = Vapor Quality Sensor



Components inside this profile
are thermally mounted to the
TTCB structure

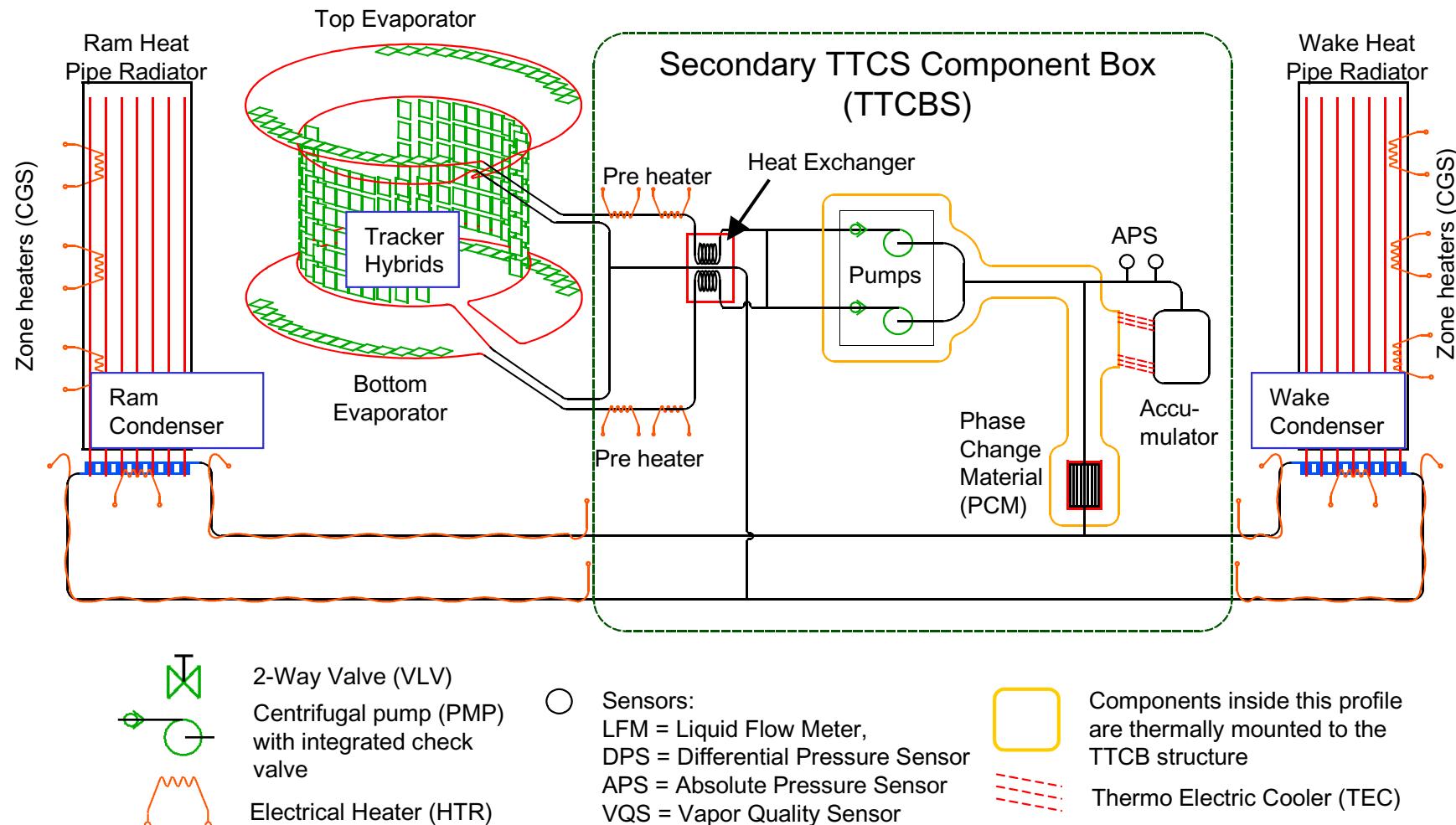


Thermo Electric Cooler (TEC)

TTCS Critical Design Review

Tracker Thermal Control System

Secondary TTCS (TTCSS)



Project Objectives: AMS-Silicon Tracker Thermal Requirements

Silicon wafer thermal requirements:

- **Operating temperature:**
-10 °C / +25 °C
- **Survival temperature:**
-20 °C / +40 °C
- **Temperature stability:**
3 °C per orbit
- **Maximum accepted gradient
between any silicon:**
10.0 °C
- **Dissipated heat:**
2.0 Watt EOL

Hybrid circuit thermal requirements:

- **Operating temperature:**
-10 °C / +40 °C
- **Survival temperature:**
-20 °C / +60 °C
- **Dissipated heat:**
**144 W total ($\pm 10\%$),
0.75 W per hybrid pair
($S=0.47$ W, $K=0.28$ W)**

Star Tracker thermal requirements:

- **Operating temperature:**
-30 °C / 40 °C
- **Survival temperature:**
-40 °C / 100 °C
- **Dissipated heat:**
6.8 W total, 3.4 W per ASTS

TTCS Thermal Requirements

TTCB (Component box) thermal requirements:

- **Operating temperature:**
-50 °C / +25 °C
- **Survival temperature:**
-50 °C / +80 °C
- **Allocated power:**
70 Watt

Evaporator thermal requirements:

- **Operating temperature:**
-20 °C / +25 °C
- **Survival temperature:**
-40 °C / +80 °C

TTCE (Control electronics) thermal requirements:

- **Operating temperature:**
-20 °C / +55 °C
- **Survival temperature:**
-40 °C / +80 °C
- **Allocated power:**
3.5 Watt

Condenser thermal requirements:

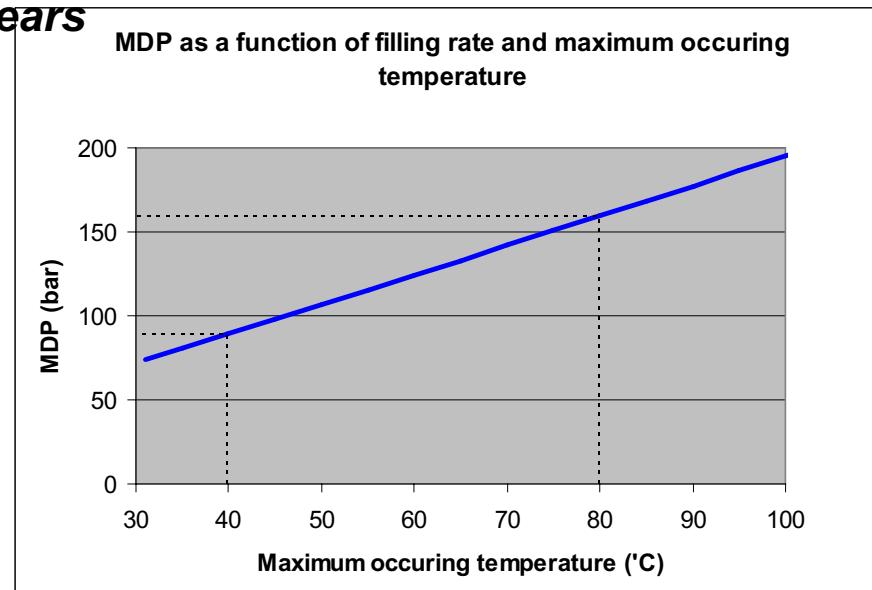
- **Operating temperature:**
-50 °C / +25 °C
- **Survival temperature:**
-100 °C / +80 °C

TTCS Structural Requirements (Applicable documents)

- **Pressurized components designed and tested according to:**
MIL-STD-1522A,
(Standard General Requirements For Safe Design And Operation Of Pressurized Missile And Space Systems)
- **Pressurized stainless steel welds are manufactured and tested according to:**
PRC-0010, Rev. A., class B.
(Process Specification for Automatic and Machine Arc Welding of Steel and Nickel Alloy Flight Hardware)
- **Pressurized aluminum welds (5083 T) will be manufactured and tested according to:**
MSFC-SPEC-504C.
(Process Specification for Automatic and Machine Arc Welding of Steel and Nickel Alloy Flight Hardware)
- **Non Pressurized hardware is designed according to:**
JSC-20545 Rev A.
(Simplified Design Options for STS-Payloads)

Other TTCS design criteria:

- **Maximum Design Pressure (MDP):** 160 bar (@ 80°C)
- **Proof Pressure 1.5 X MDP** 240 bar
- **Burst Pressure 2.5x MDP (comp)** 400 bar
- **Burst Pressure 4 x MDP (tubing)** 640 bar
- **TTCS Volume per system:** 1.9 Liter
- **Accumulator Volume** 1.3 Liter
- **TTCS CO₂ filling per system:** 874 gram
- **Allowed system leak rate:** 1*10⁻⁶ mbar*l/s
- **Mission duration:** 5 Years



TTCS Certification testing

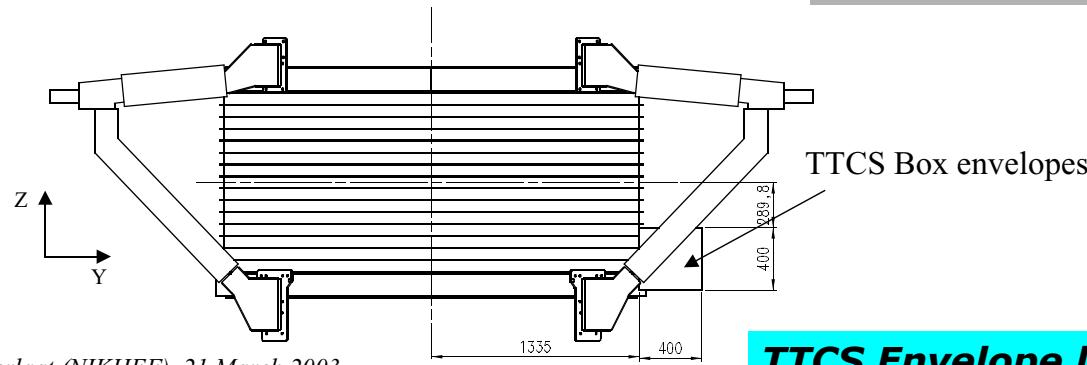
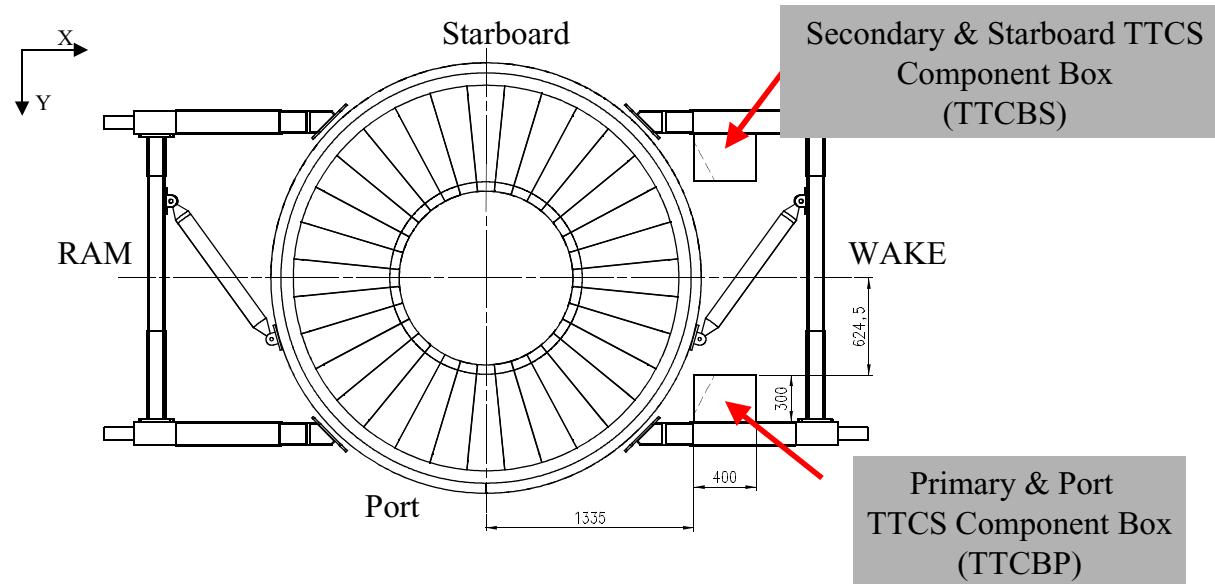
Thermal performance tests:

- **In Vacuum:**
 - Thermal Bars
 - TTCS Box
 - Complete TTCS during the AMS-02 overall thermal vacuum testing.
- **In the normal atmosphere (Insulated):**
 - Full scale development breadboard model
 - Flight hardware system testing using a cold plate (Radiator removed)

Structural testing:

- **Proof pressure (1.5x MDP) on flight hardware (Components, TTCS assembly)**
- **Burst pressure tests using non-flight hardware (On components only TBC)**
- **Leak testing:**
 - Helium leak tests on flight components
 - Pressure decay test on the complete TTCS after proof pressure testing
- **Vibration testing:**
 - All hardware is designed to be above a 1st resonance frequency of 50 Hz, no vibration testing is necessary for structural certification. However the following items will undergo vibration testing for mission success reasons:
 - Thermal bars (Prototype hardware)
 - TTCB (Component box)
 - TTCE (Electronics crate)

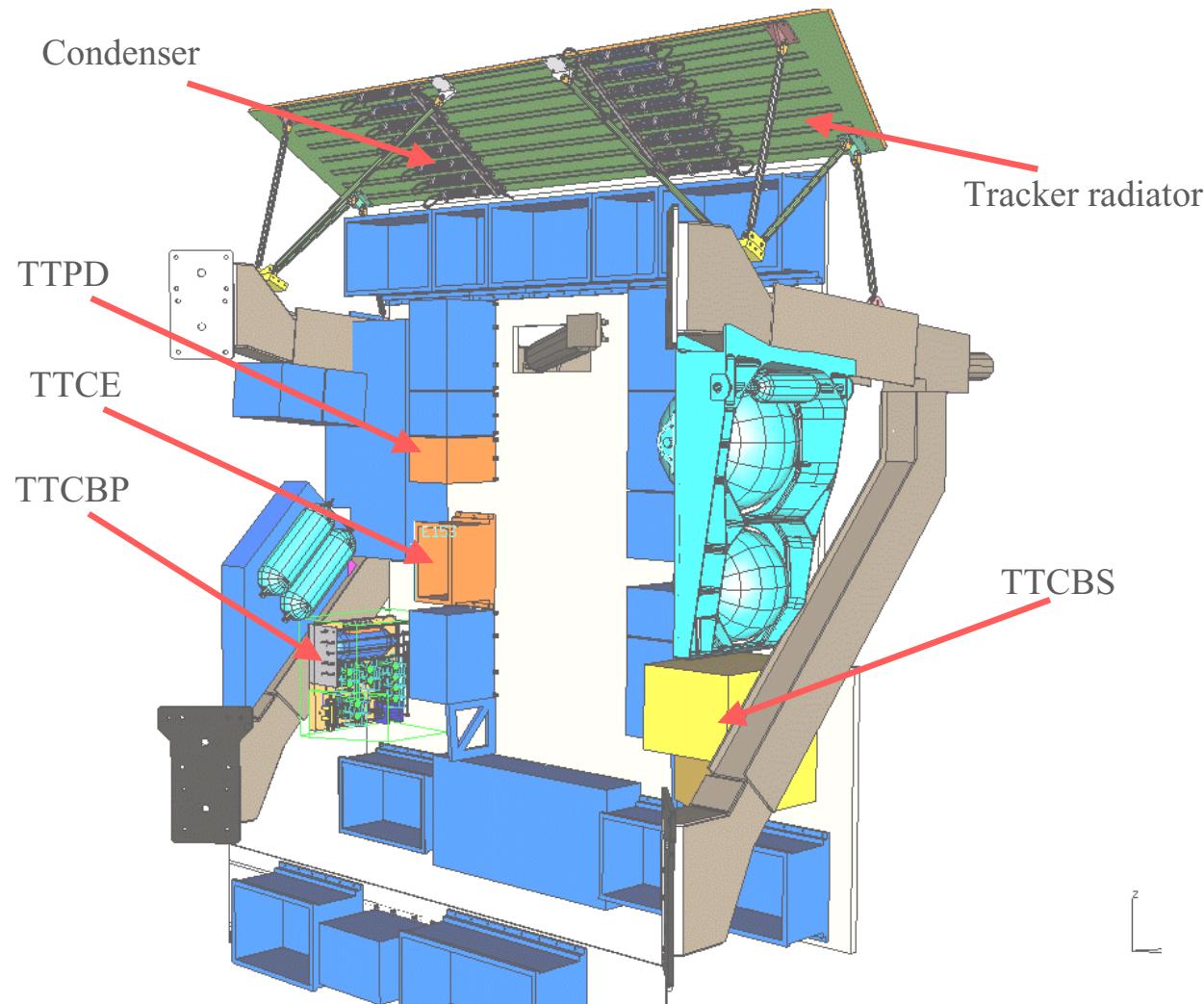
TTCS System Overview



B. Verlaat (NIKHEF), 21 March 2003

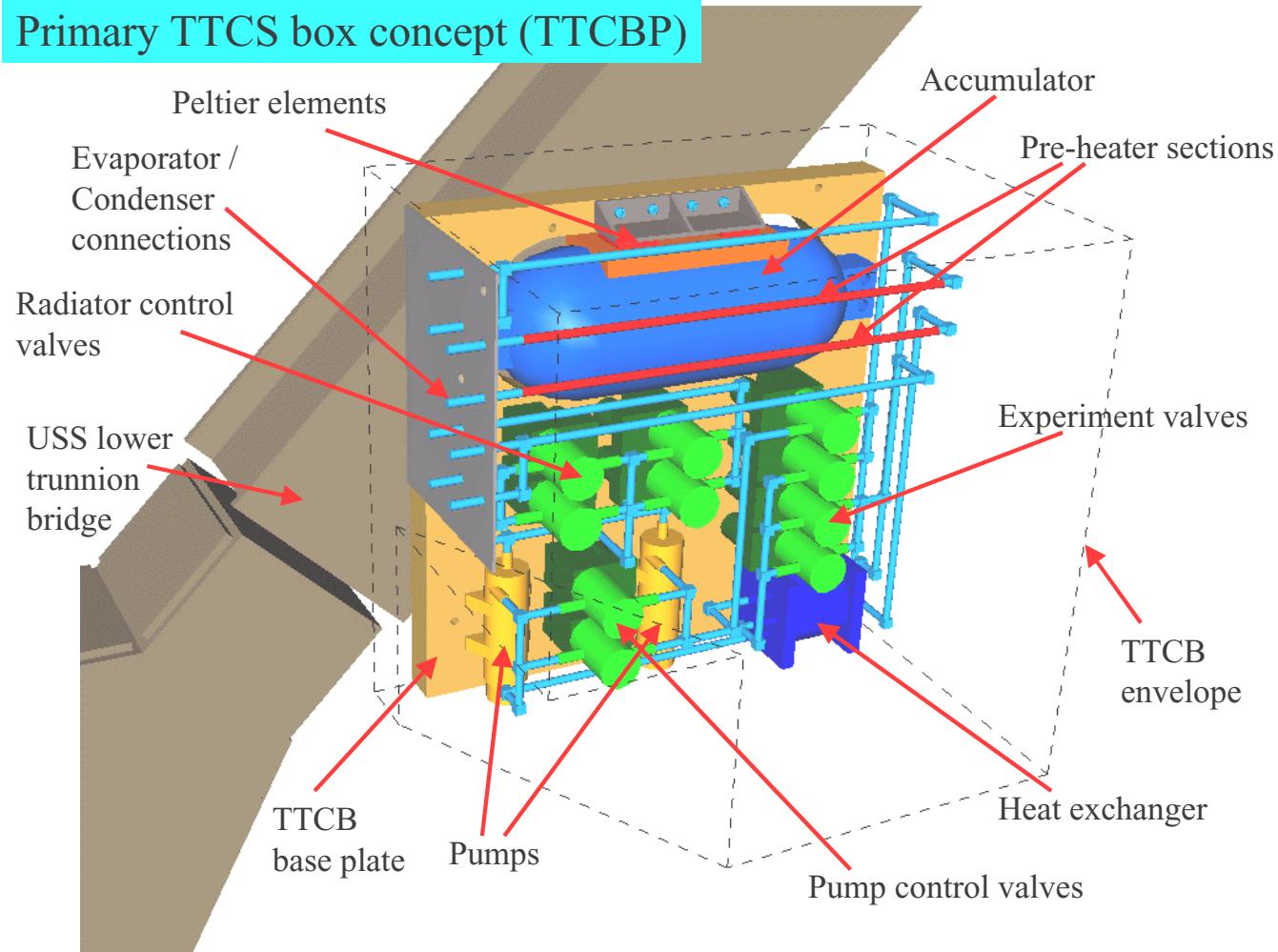
TTCS Envelope location

TTCS System Overview



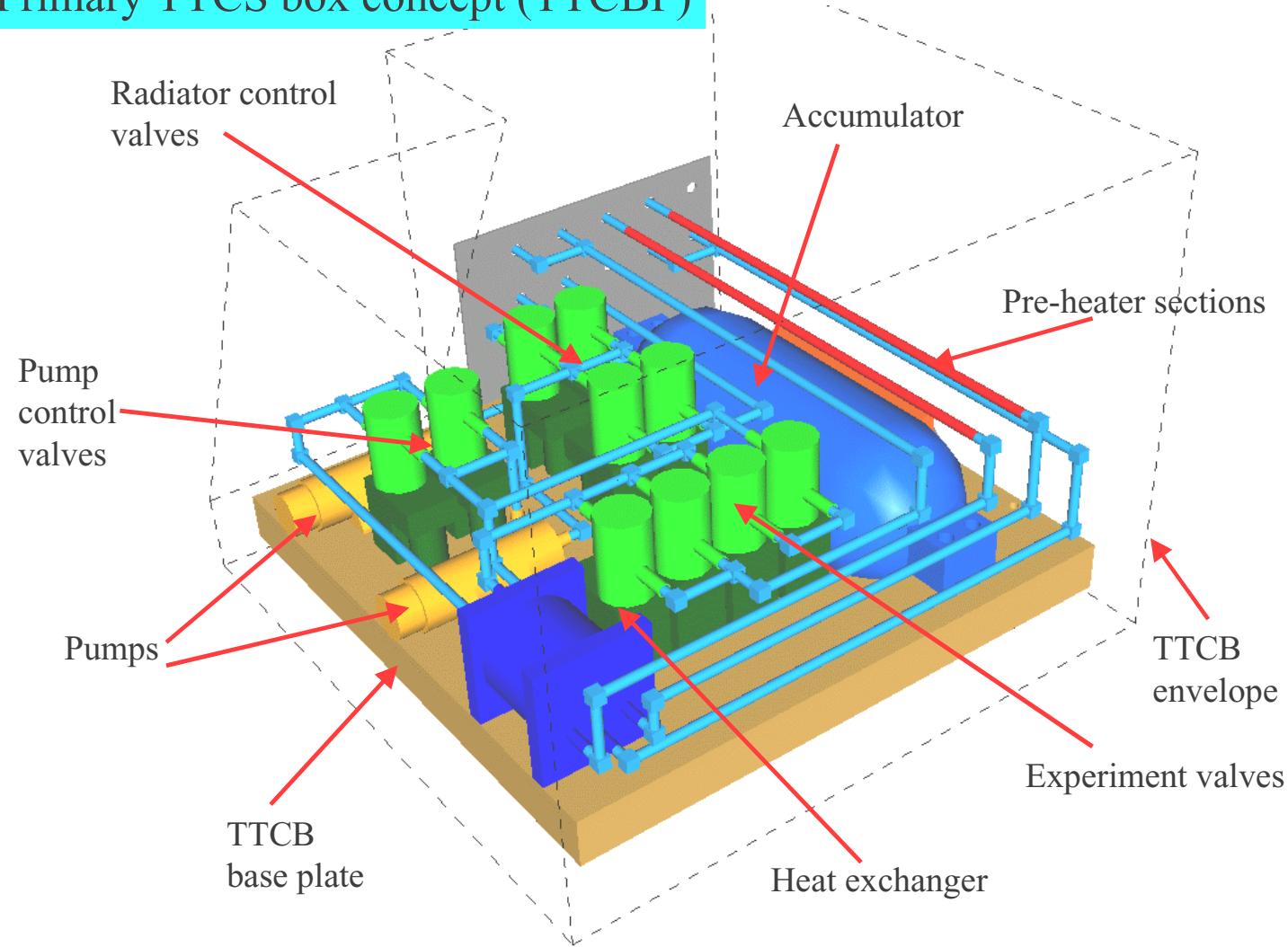
TTCS System Overview

Primary TTCS box concept (TTCBP)



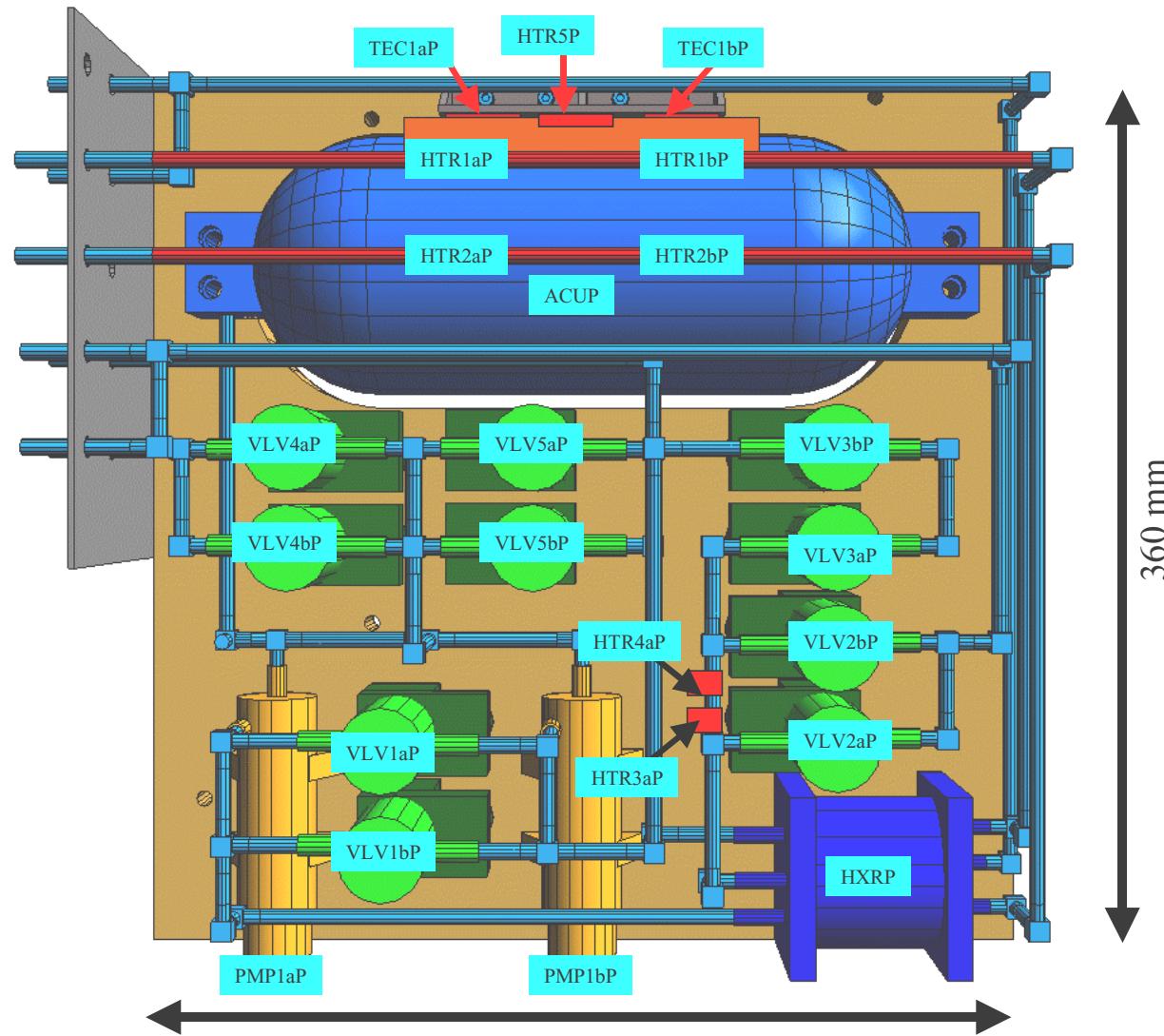
TTCS System Overview

Primary TTCS box concept (TTCBP)



TTCS System Overview

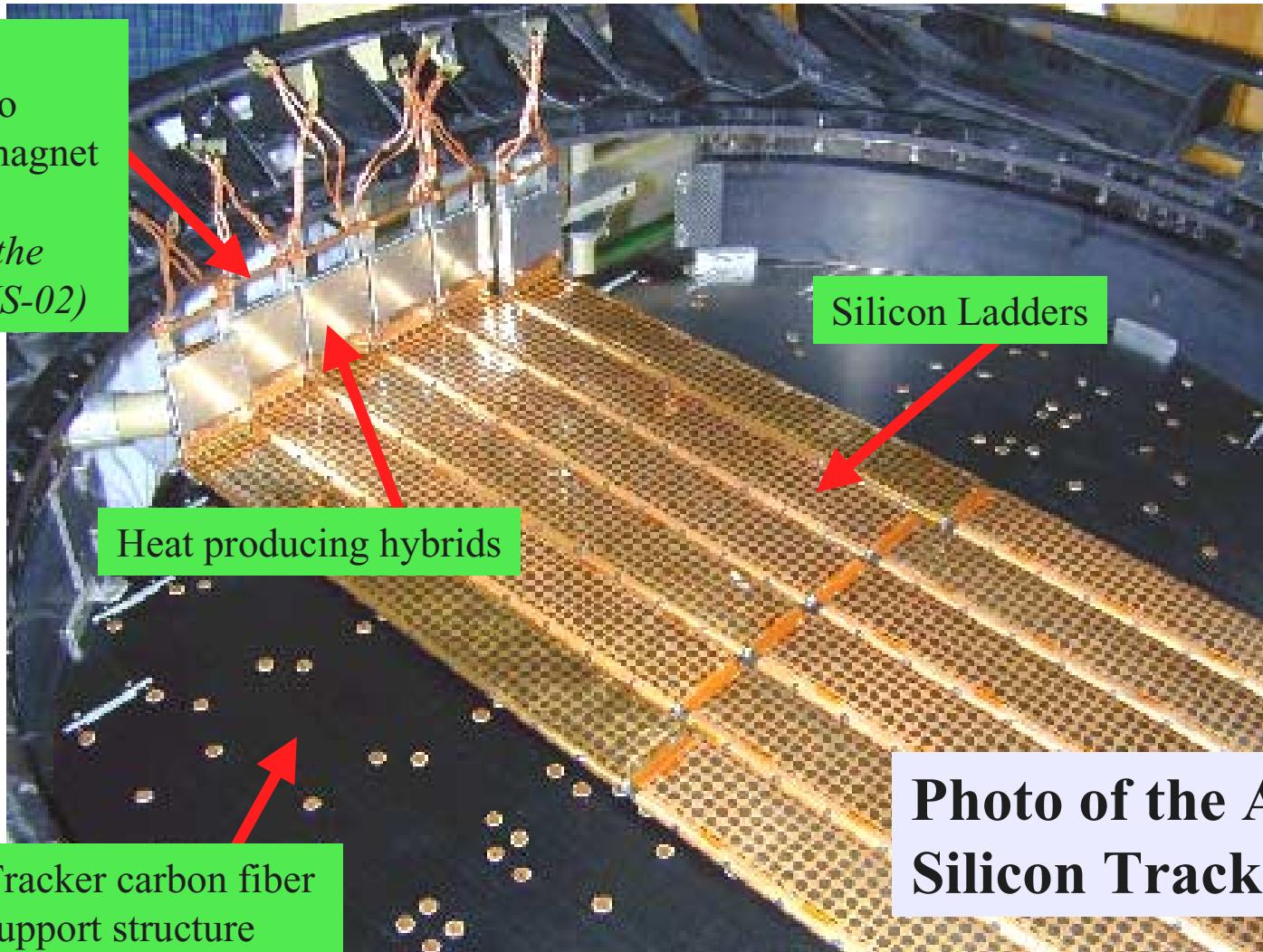
TTCBP



System Overview

For similarity, AMS-02 Tracker lay-out similar to AMS-01

Thermal bar connection to permanent magnet
(Will be the interface to the TTCS in AMS-02)



**Photo of the AMS-1
Silicon Tracker**

System Overview Component Functionality

Pump	<ul style="list-style-type: none"> Transport the fluid through the loop.
Accumulator	<ul style="list-style-type: none"> Regulate the evaporator temperature in the tracker Account for the expansion of the working fluid
Accumulator Peltier elements	<ul style="list-style-type: none"> Regulate evaporation set-point in all operation modes
Accumulator heaters	<ul style="list-style-type: none"> Emergency accumulator heat-up in case liquid line temperature approaches saturation temperature (to avoid cavitation in pump)
Valves (exp. section)	<ul style="list-style-type: none"> Change from between loop configurations
Valves (liquid line)	<ul style="list-style-type: none"> Control the mass flow distribution between Wake and RAM radiator (under discussion)
Heat Exchanger	<ul style="list-style-type: none"> Exchange heat between hot evaporator outlet and cold evaporator inlet. Reduction of pre-heater power
Evaporator	<ul style="list-style-type: none"> Collect heat at the tracker electronics. The evaporation process provides the temperature stability required.
Condensers	<ul style="list-style-type: none"> Remove the heat from the working fluid to the radiators. The condensing process makes the heat transfer effective.

System Overview Component Functionality

Absolute Pressure Sensors	<ul style="list-style-type: none"> Monitor the absolute pressure inside the loop
Differential Pressure Sensor	<ul style="list-style-type: none"> Monitor pump pressure head
LMF	<ul style="list-style-type: none"> Monitor mass flow
PCM (deleted)	<ul style="list-style-type: none"> Lower pre-heater power peaks
Pre-heaters	<ul style="list-style-type: none"> Heat evaporation liquid inlet to saturation point
Dallas Temperature Sensors	<ul style="list-style-type: none"> Monitor temperatures TTCS temperatures
Pt1000 Temperature Sensors	<ul style="list-style-type: none"> Control pre-heater power Control accumulator temperature Control liquid line valves (under discussion)

TTCSP Component overview

Inside TTCBP

- *2x Pump (PDT Model 5059-1; 2-Stage centrifugal pump with integrated check valves)*
- *10x (or 6x)Proportional two-way valves (Bradford Engineering)*
- *1x Accumulator (1.3 Liter), (Self engineered)*
- *1x Three volume heat-exchanger (Self engineered)*
- *2x Peltier elements (Supplier: Melcor CP1.0-127-05L (30x30mm) 2 electrically in series)*
- *3x Liquid flow meter (Via Differential pressure using Keller PD-23 or Validyne DP 10 TBC)*
- *2x Absolute pressure sensor (Supplier: Keller PA-23/25)*
- *1x Differential pressure sensor (Supplier: Keller PD-23)*
- *416 Dallas temperature sensors (Dallas DS18S20/TO92)*
- *36 PT100(0) temperature sensors (Supplier TBD)*
- *10x Electrical shielded resistance wire heaters (Supplier: Thermocoax)*

Outside TTCBP

- *2x Evaporator assemblies (Self engineered)*
(Evaporator is qua design the only common shared hardware between the primary and the secondary TTCS)
- *2x Condenser (Self engineered)*
- *Thermal control electronics in TTCE crate on wake radiator (Self engineered)*

TTCSP Overview

- *All thermal hardware in the TTCSP except for pre-heaters (TBC)*
- *Valves to create experimental cases and thermal control cases*
- *Different evaporator concepts possible due to valves.*
 - *Parallel operated evaporators*
 - *1 pump per evaporator*
 - *Serial operated evaporators*
 - *Evaporator by-pass for thermal experiments*
- *Condenser optimization*
 - *Too cold or too warm condensers can be closed or restricted by valves*
- *Valves are redundant such that in case of a single failure the TTCSP is still functioning at a level better than the secondary TTCS (Which has no actuators other than the pumps). Only experimental or optimization cases are affected.*

TTCSS Overview (*Schematic layout is shown on page 6*)

- *All thermal hardware in the TTCS except for pre-heaters (TBC)*
- *No actuated valves*
- *1 evaporator concept possible:*
 - *Parallel operated evaporators only*
- *No Condenser optimization possible.*
- *Due to the absence of control valves the secondary TTCS will show a worse thermal performance than the primary. (More pre-heat power)*
- *The secondary is more simple (No active components other than the pumps) thus more reliable than the primary TTCS.*
- *No sensors (other than the APS) are in the pressurized volume.*

TTCS Main material and construction overview

General materials

- *Tubes: CRES 316L*
- *Evaporator bridges :OFHC Copper*
- *Condenser profiles: AA 5083*
- *Refrigerant: CO₂ (R744)*
- *Bolts: CRES A286 (#10 and above) and CRES 316 (up to M4)*
- *Thermal spacers: G10 and Teflon*
- *Support brackets: AA 6061*
- *Insulation: MLI*

General construction

- *Pressurized volume is an all welded sealed system. Weld types included are:*
 - *Gas Tungsten Arc Welding (Orbital welding)*
 - *Laser welding*
 - *Inertia welding (Aluminum to stainless steel)*
- *Connectors are foreseen (Candidate connector supplier: Dynatube)*
- *Thermal interface connection of copper heat sinks to stainless steel tubes by soft soldering with Sn96Ag filler.*
- *Glued interfaces using AV138m/HV998 glue (Thermal joints, non structural)*
- *Use of NASA provided bolts from #10. (Use of self provided metric bolts up to M4)*

Components: Pump

- System design, tubing selection & pump performance

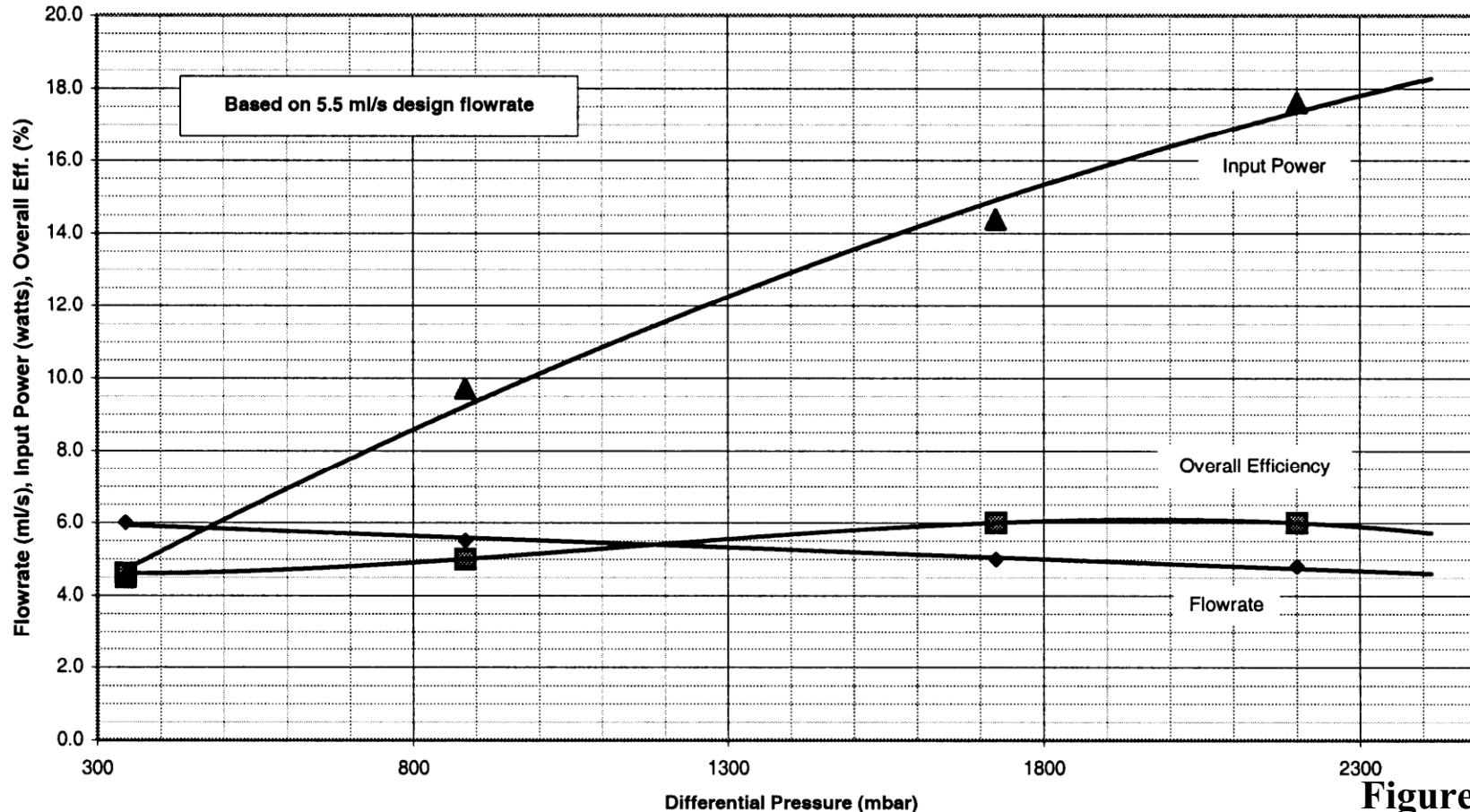
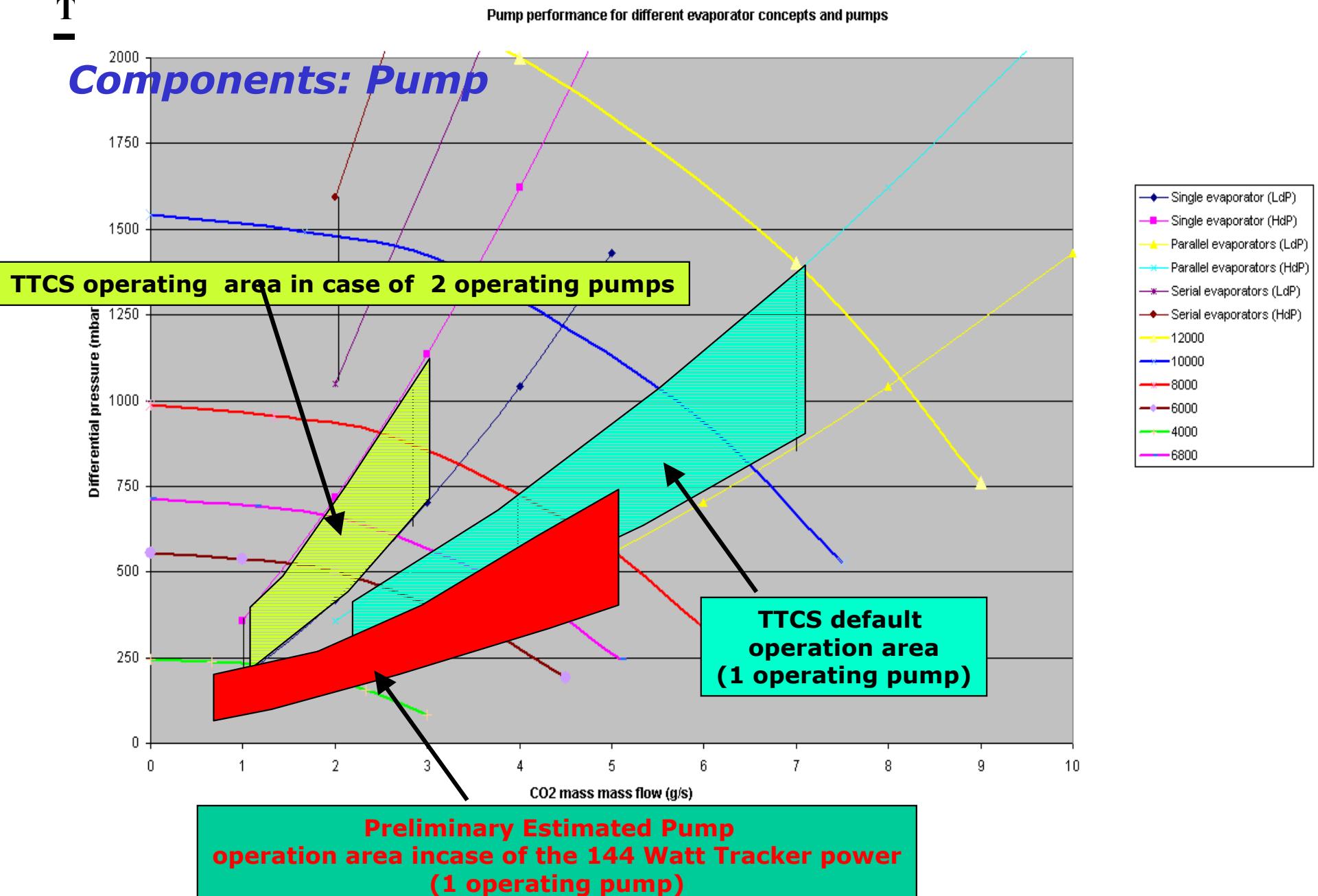


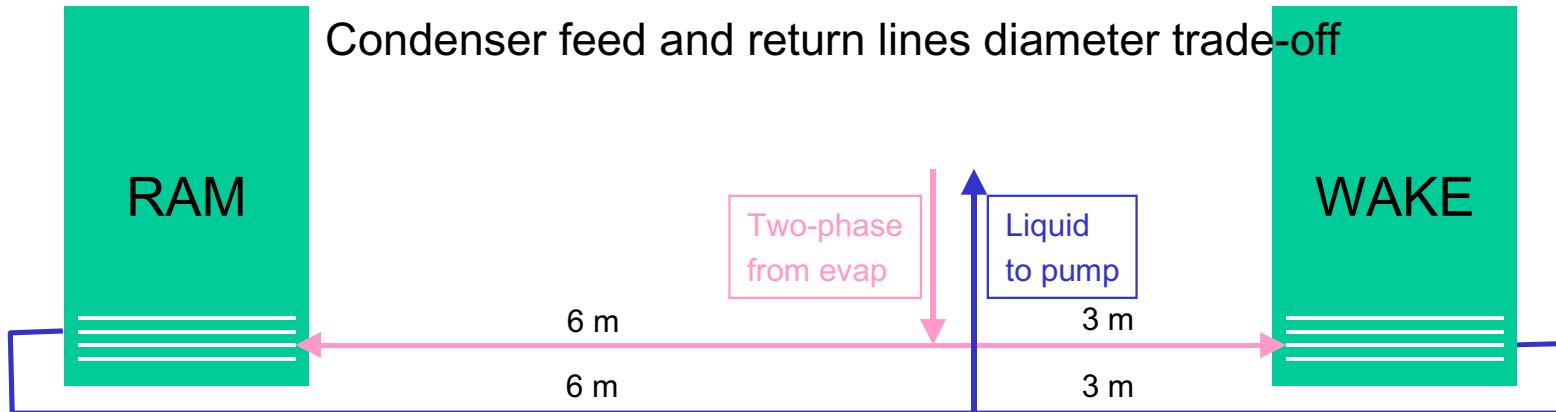
Figure by PDT

Figure 2.0 - Model 5059 Calculated Pump Performance Curve

T



Components: Pump



Advantage <u>small</u> diameter	Advantage <u>large</u> diameter
<ul style="list-style-type: none"> Lower loop volume <ul style="list-style-type: none"> smaller accumulator (lower mass) lower accu control power req'd Higher pressure drop fits better in current pump operating range Less or no slug flow during 1-g testing Easier integration (easier bending) 	<ul style="list-style-type: none"> Condenser pressure drop is dominant <ul style="list-style-type: none"> Better natural condenser branch flow distribution (if hot condenser vapour front increases, pressure drop will rise, and mass flow through the colder one will increase)

Components: Pump

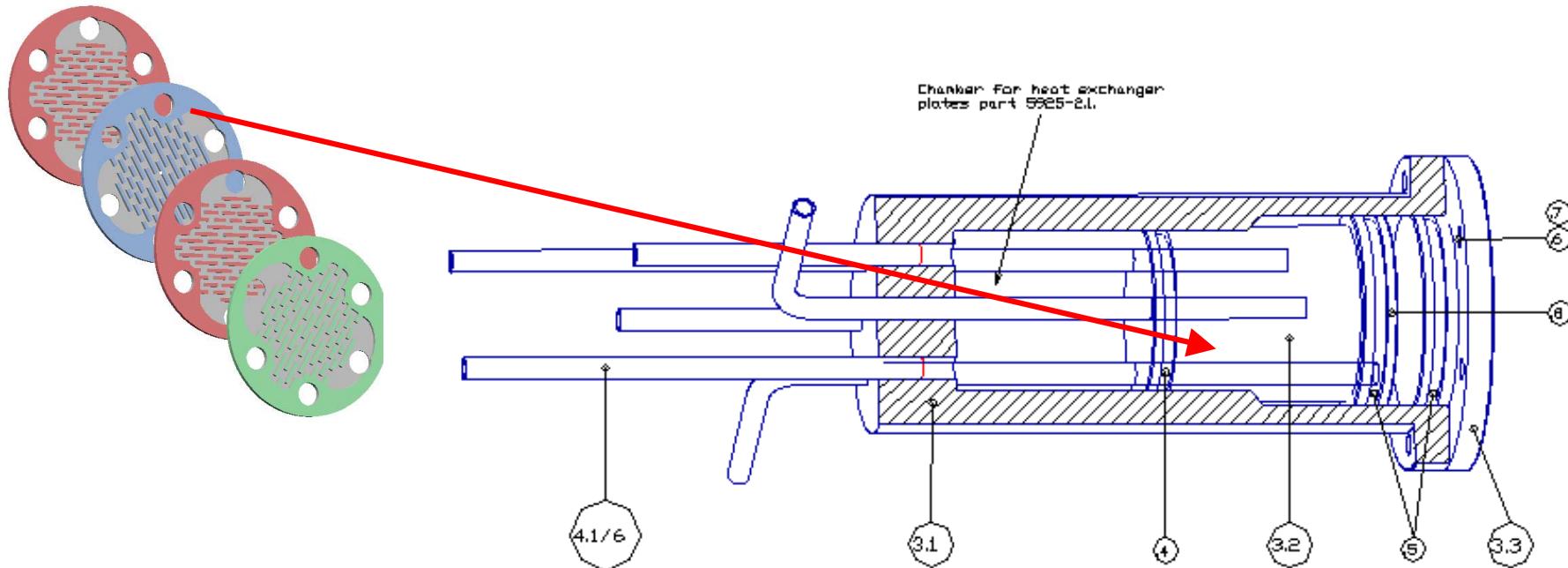
Close co-operation with PDT (pump supplier) is required to:

- Update system design to new situation $\Phi_v = 2 \text{ g/s}$, $\Delta P = 100 \text{ mbar}$
- Optimise hydraulic system to shift to an optimum pump operating range, as the pump is the most critical component

Components: Heat Exchanger

Heat Exchanger

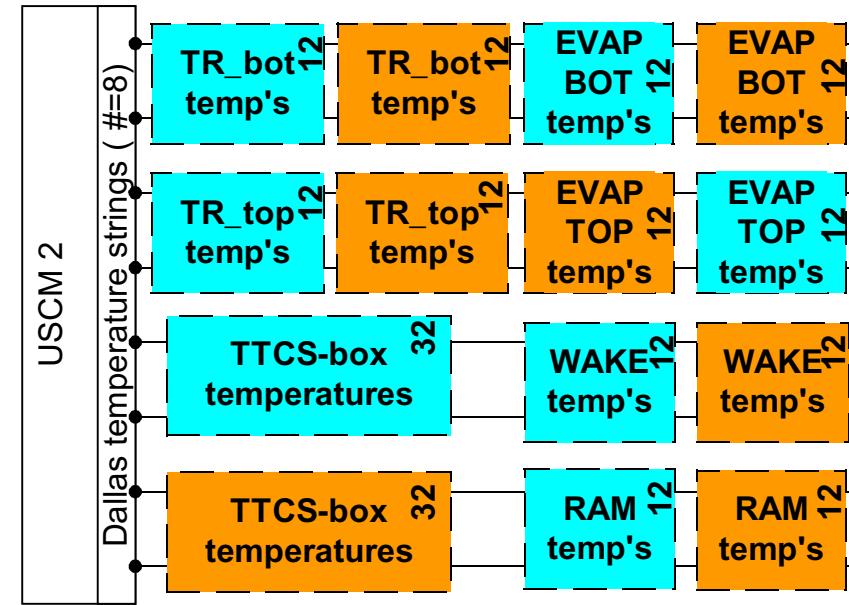
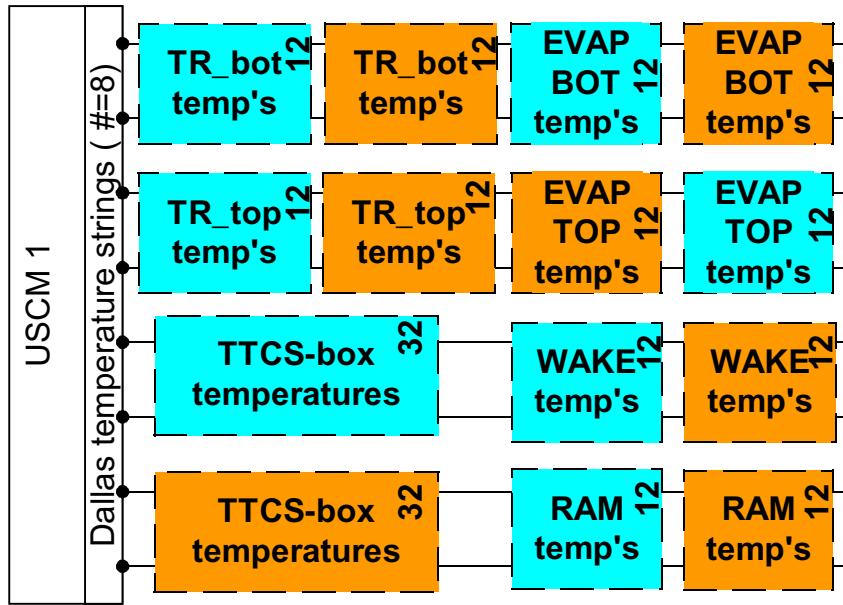
- Heat exchanger successfully tested
- $\Delta P_{\text{vapour}} = 5 \text{ mbar}$, $\Delta P_{\text{liquid}} = 1 \text{ mbar}$ (at 3 g/s n=6)



Components: Tubing (presented by B. Verlaat)

- **Routing and AIT approach Dallas sensors**
- **Routing piping**
 - **to/from radiators along unique support structure**
 - **Tube support beam is used for transport from top to bottom outer cylinder**

Components: Dallas Sensors



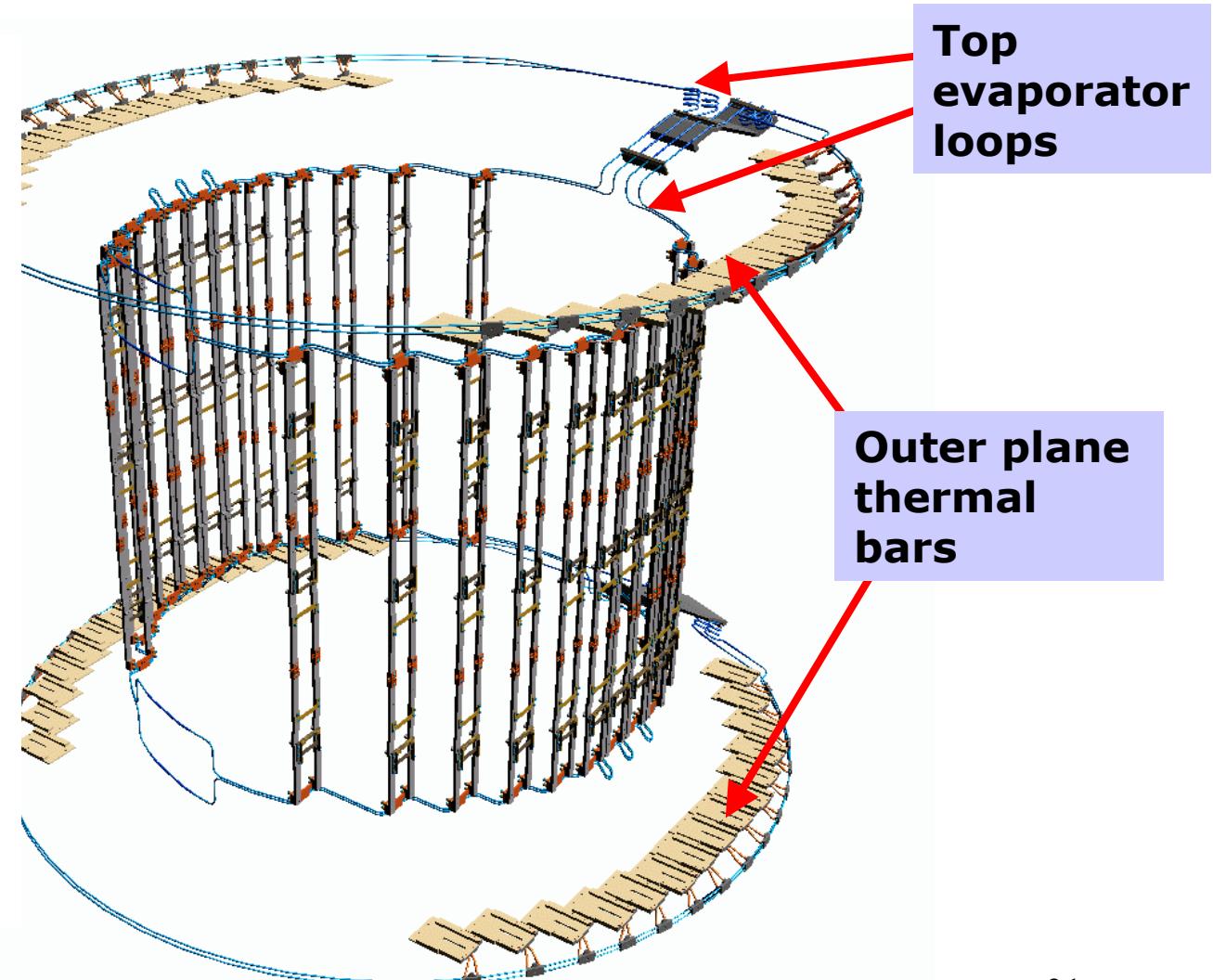
Primary loop Secondary loop

- Trade between redundancy and wiring complexity
- The Dallas DS1820 T-sensors are grouped by location on the TTCS
- Each group of sensors will be read out by 2 strings. By sorting the groups the complexity and length of string will be minimised.

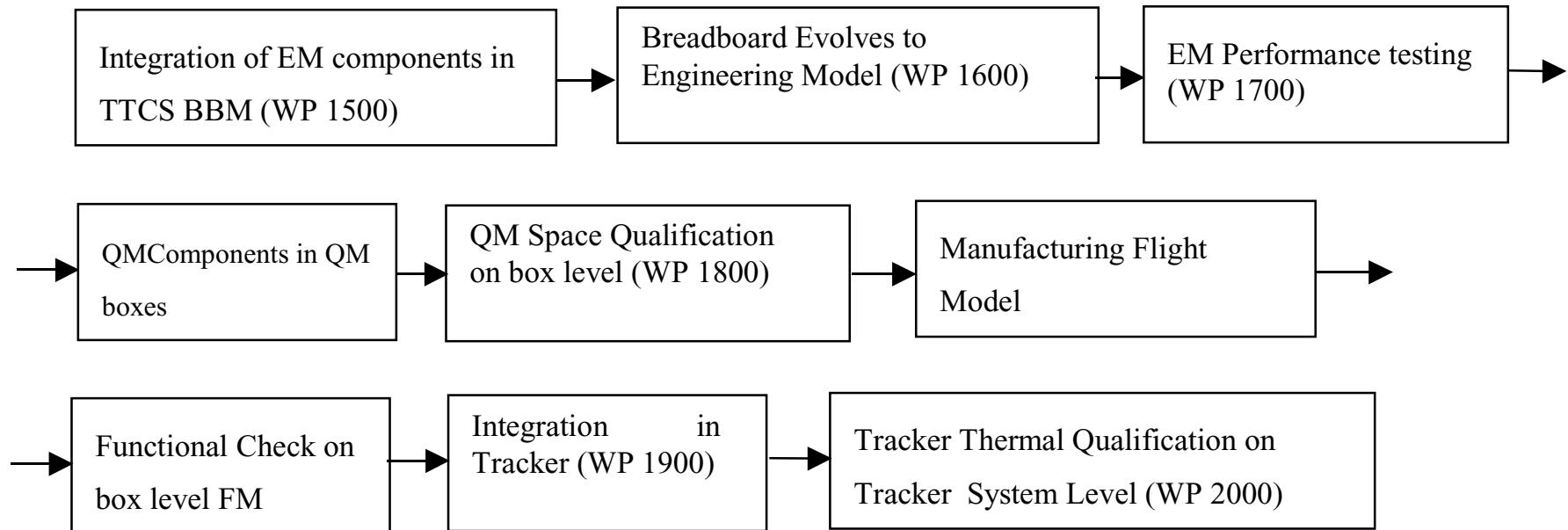
Components: Evaporator (presented by B. Verlaat)

Evaporator

- Evaporator welding is started
- Copper bridges design ready and milling will start this year



Model and Test & Verification Approach



Model Philosophy: BBM, EM, QM, FM/FS

Model Philosophy

- BBM, EM, QM, FM/FS

System level	BBM	EM	QM	FM	FS
TTCS (complete system)	2	1/2(1)	-	1	-
(Sub)-System	BBM	EM	QM	FM	FS
TTCS-P Box		1	1	1	1
TTCS-S Box		1	1	1	1
Evaporator subsystem		½	½	1	-
Condenser subsystem		½	½	1	½
TTCE	2	1	1	1	-
TTPD	1(2)	1(2)	1	1	-

Planned models on System level and Box level

Model and Test & Verification Approach

Component	BBM	EM	QM	FM	FS
Pump	-	2	1	4	1
Accumulator	-	1	1	2	1
Valves (exp. section)	-	6(12)	6	6	2
Valves (liquid line)	4	4(8)	4	4	2
Heat Exchanger	1	1(2)	2	2	1
Absolute Pressure Sensors	1	2(4)	4	4	2
Differential Pressure Sensor	1	2(4)	4	4	2
LFM	3	3(6)	6	6	2
Pre-heaters	4	4(8)	8	8	2
Dallas Temperature Sensors	208	416			
Pt1000 Temperature Sensors	18	18(36)	36	36	9
NLR-experiment	1	1 (0)	1	1	1

Planned Models component level

Model and Test & Verification Approach

- Levels of verification
 - Tracker TCS level
 - TTCS-Box level
 - TTCS-P box
 - TTCS-S box
 - TTCE-box
 - TPPD-box
 - Component level
 - Pump etc
 - Electronic boards (TTEI, TTEC, TPPC, TTPT)
- Qualification tests are mainly performed on box level
- Critical components are also qualified on component level

Model and Test & Verification Approach

System level	Functional Test	Vibration/ Shock	TV-Test	EMC/EMI	By
TTCS integrated in AMS	X	X (TBC)	X	-	AMS/SYS/NLR
Subsystem level	Functional Test	Vibration/ Shock	TV-Test	EMC/EMI	By
TTCS-P Box	X	X	X	X	TBD
TTCS-S Box	X	X	X	X	TBD
Evaporator subsystem	- (TBC)	X (on top-half) TBC	S	-	TBD
Condenser subsystem (4x)	X Hydraulic and Thermal	X Combined with radiator?	S	-	TBD
TTCE	X	X	X	X	TBD
TTPD	X	X	X	X	TBD

Verification tests on system and box level

- X: Test performed on given level
- B: Test performed on box-level
- A: Test performed on AMS-level

Model and Test & Verification Approach

Components	Functional Test	Vibration/ Shock	TV-Test	EMC/EMI	By
Pump	X	X	X	X	PDT
Accumulator	X	X	X	X	Supplier
Valves (exp. section)	X	B	B	B	TBD
Valves (liquid line)	X	B	B	B	TBD
Heat Exchanger	X	TBD	-	-	TBD
Absolute Pressure Sensors	X	B (TBC)	B	B	TBD
Differential Pressure Sensor	X	B (TBC)	B	B	TBD
LFM	X	B	B	B	TBD
Pre-heaters	X	B	B	B	TBD
Dallas Temperature Sensors	X	B	B	B	TBD
Pt1000 Temperature Sensors	X	B	B	B	TBD
NLR-experiment	X	X	B	B	NLR

Verification tests component level

- X: Test performed on given level
- B: Test performed on box-level
- A: Test performed on AMS-level

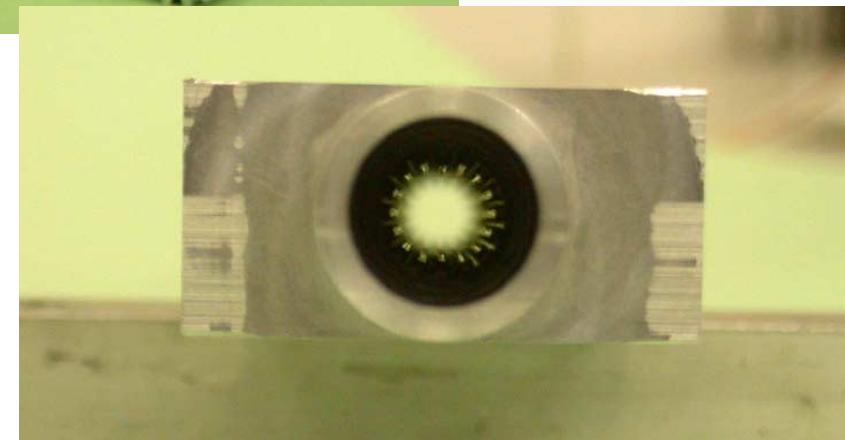
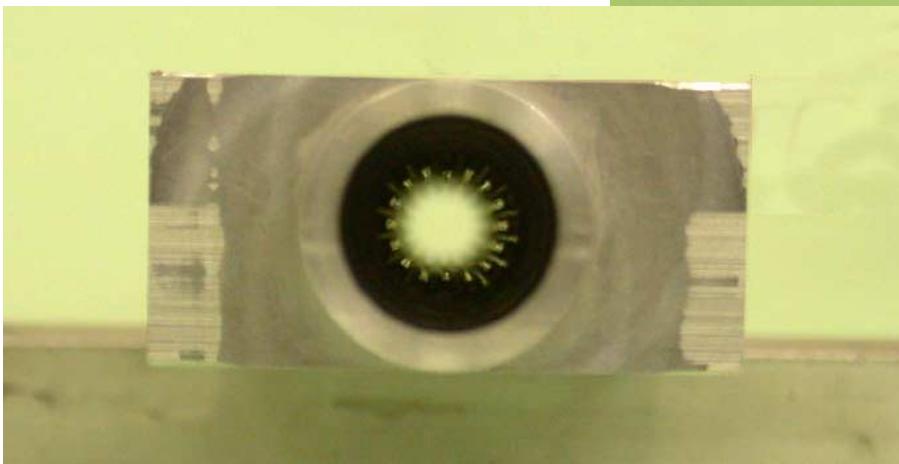
Condenser design and freezing



Condenser profile, bi-metal SS-Al end pieces
and profile filler rod with grooved end

Condenser design and freezing

Alu 5083 will
replace current
Alu 6061



Detail of condenser profile (grooved inside visible),
bi-metal SS-Al end piece and grooved end of filler rod

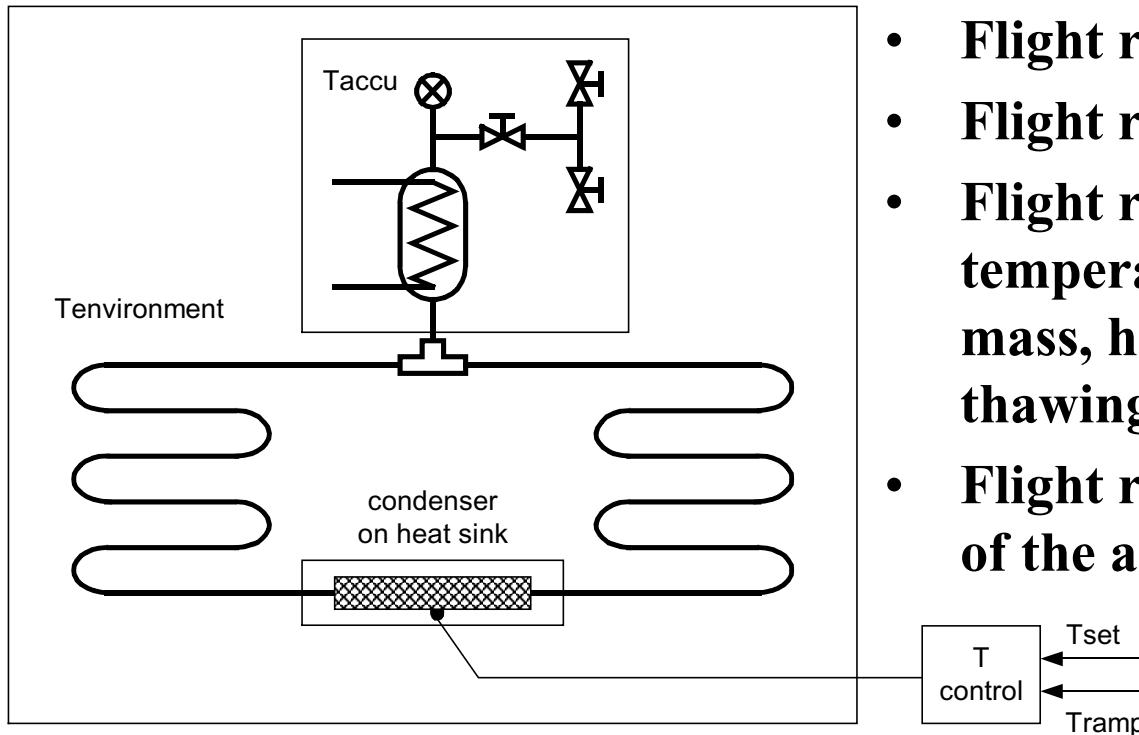
Freezing Problem Description and Test Objective

- In case of total power loss in orbit part of the CO₂-loop may freeze (CO₂ freezes at -55 °C)
- The impact of uncontrolled melting on loop tubing leak-tightness is unknown
 - uncontrolled heating can occur by solar heat input

Test Objective

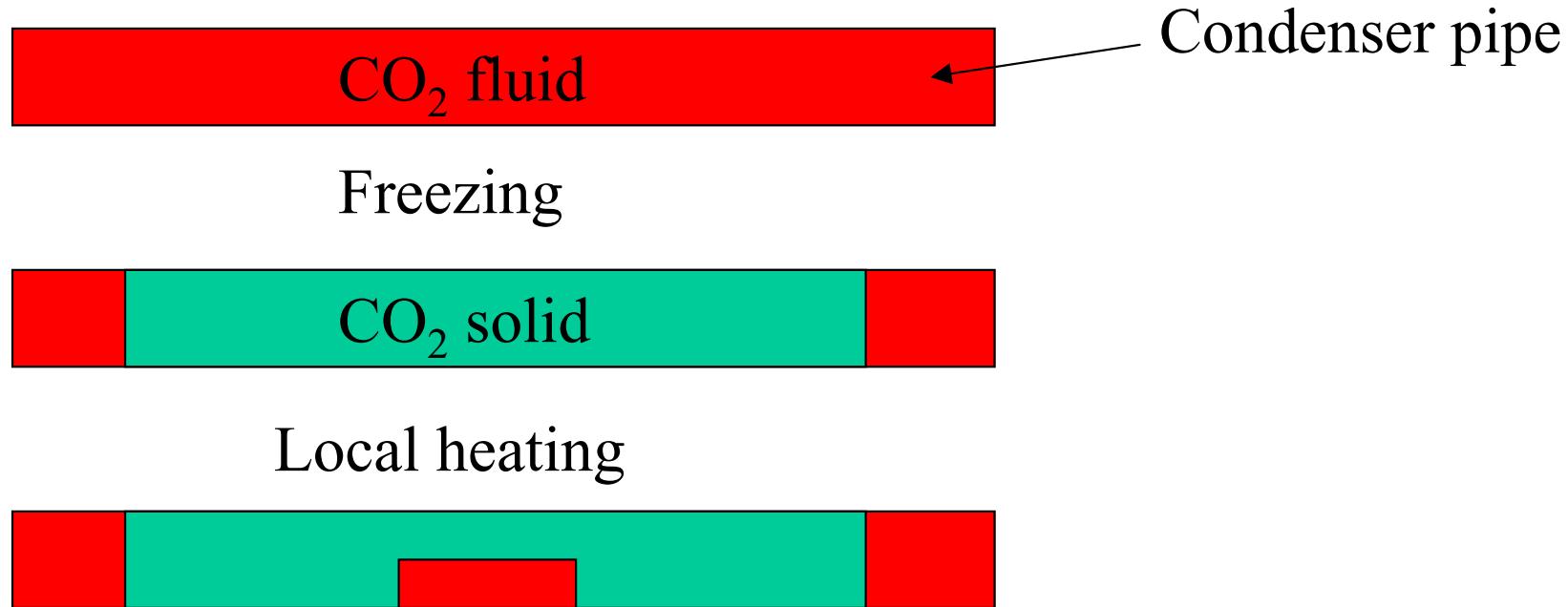
- Investigation of CO₂-melting on the loop tubing leak tightness

Components: Condenser Freezing test



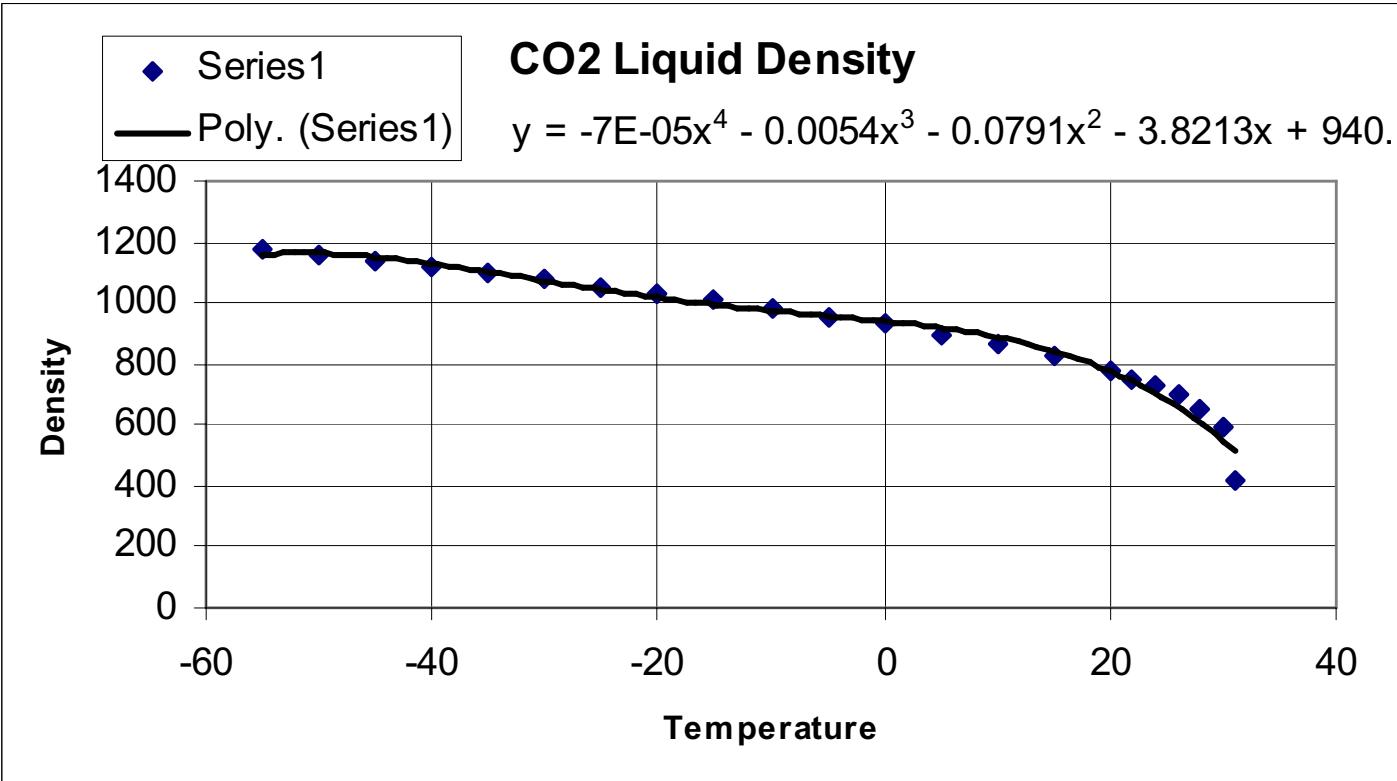
- Flight representative condenser lay-out
- Flight representative tubing properties
- Flight representative expected temperature rate of change (radiator mass, heat load) during freezing and thawing.
- Flight representative temperature of the accumulator

Problem Description and Test Objective



--> local high pressures, a possible thread
 to leak tightness condenser construction

Properties CO_2



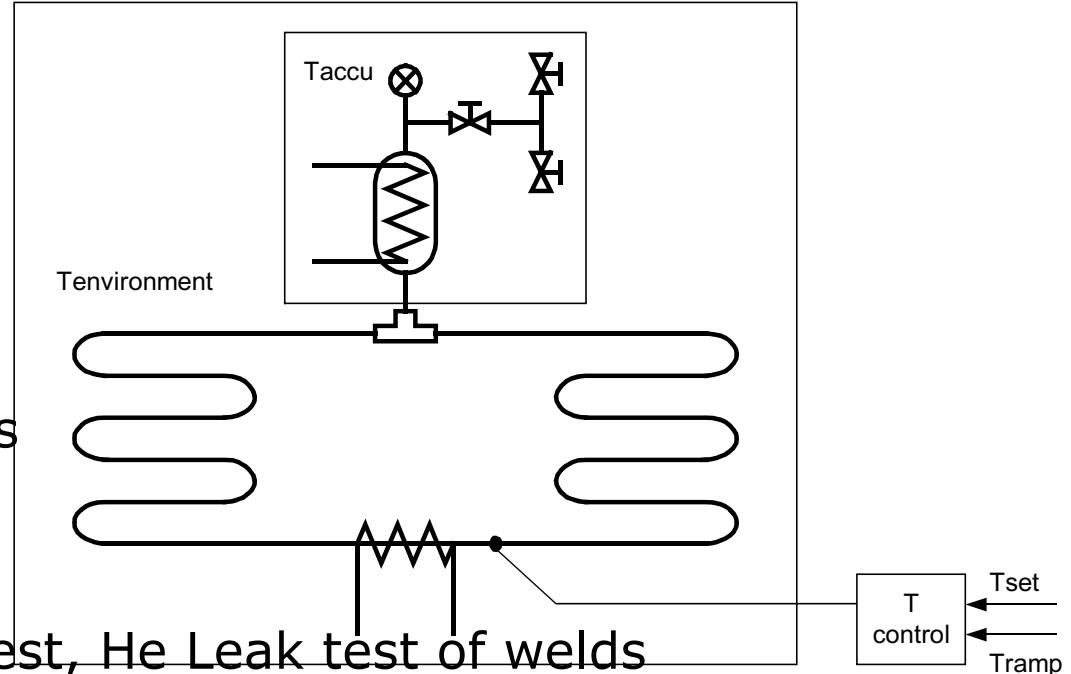
- Level of CO_2 high pressure is uncertain ---> test
- ρ_{solid} increases with decreasing temperature (\rightarrow 8 hours dwell₄₃)

Test Approach

- Downscaled loop will be built and tested in environment below freezing point.
- Temperature controlled accumulator and representative tubing of 3 to 5 m in length.
- Minimisation of couplings, branches and intrusive test components will be avoided to avoid accidental leak.
- Loop is pressurised by controlling the accumulator temperature during complete test.
- After 8 hours dwell time the condenser will get a preset temperature ramp to a temperature above freezing point.
- Environment temperature will be gently increased to ambient to allow inspection.

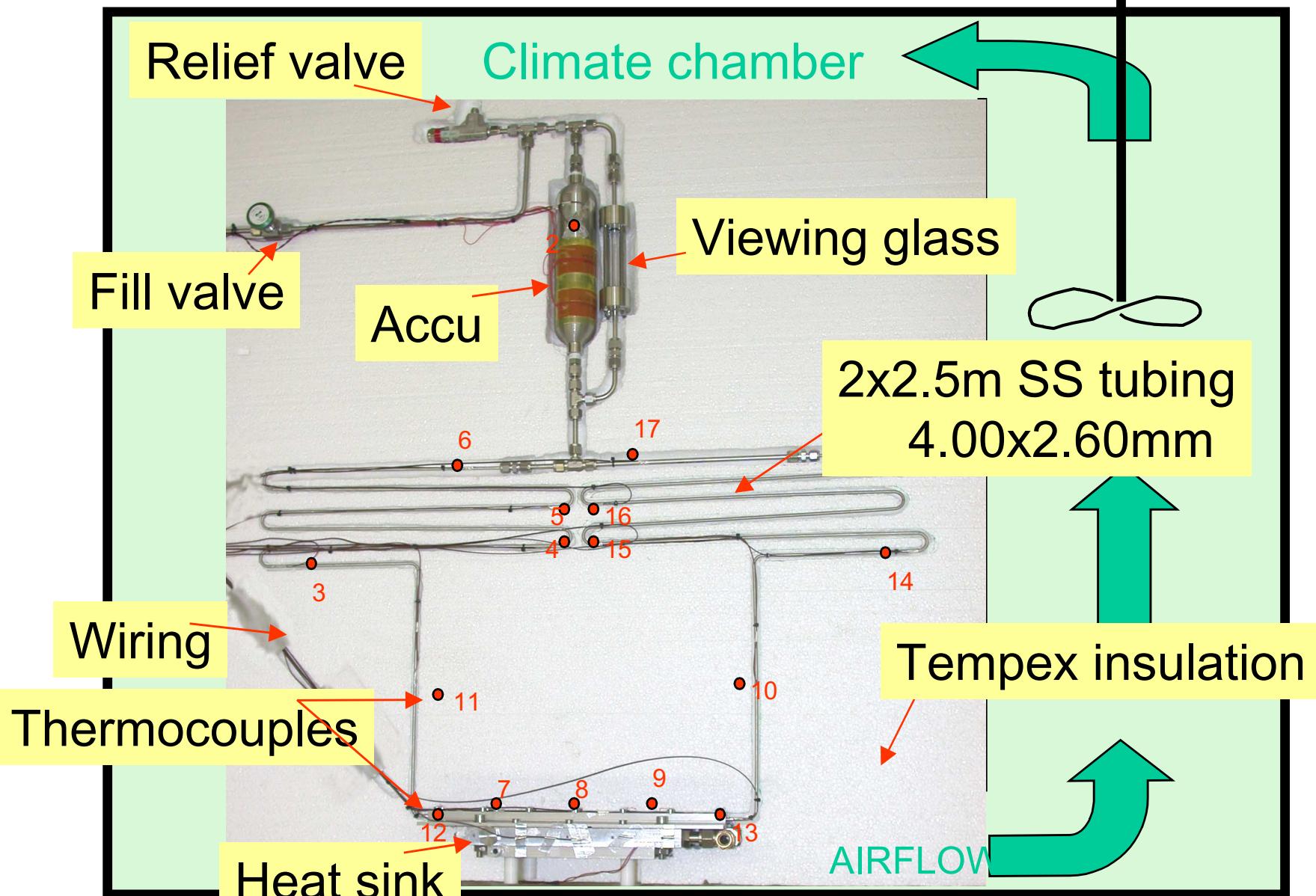
Test Sequence

- First test with tubing
 - test test set-up
 - avoid loss of expensive condenser
 - reference for leak tightness
- Second test with flight-like condenser
 - Proof pressure (240 bar) test, He Leak test of welds
 - Strain gauges reference pressure test (verify strain with known inner pressure)
 - Freezing test, proof pressure test, He leak test.
- Fail/Pass Criterium
 - Difference between He-leak test prior and after test
 - With strain gauges no pressure should be detected above MDP.



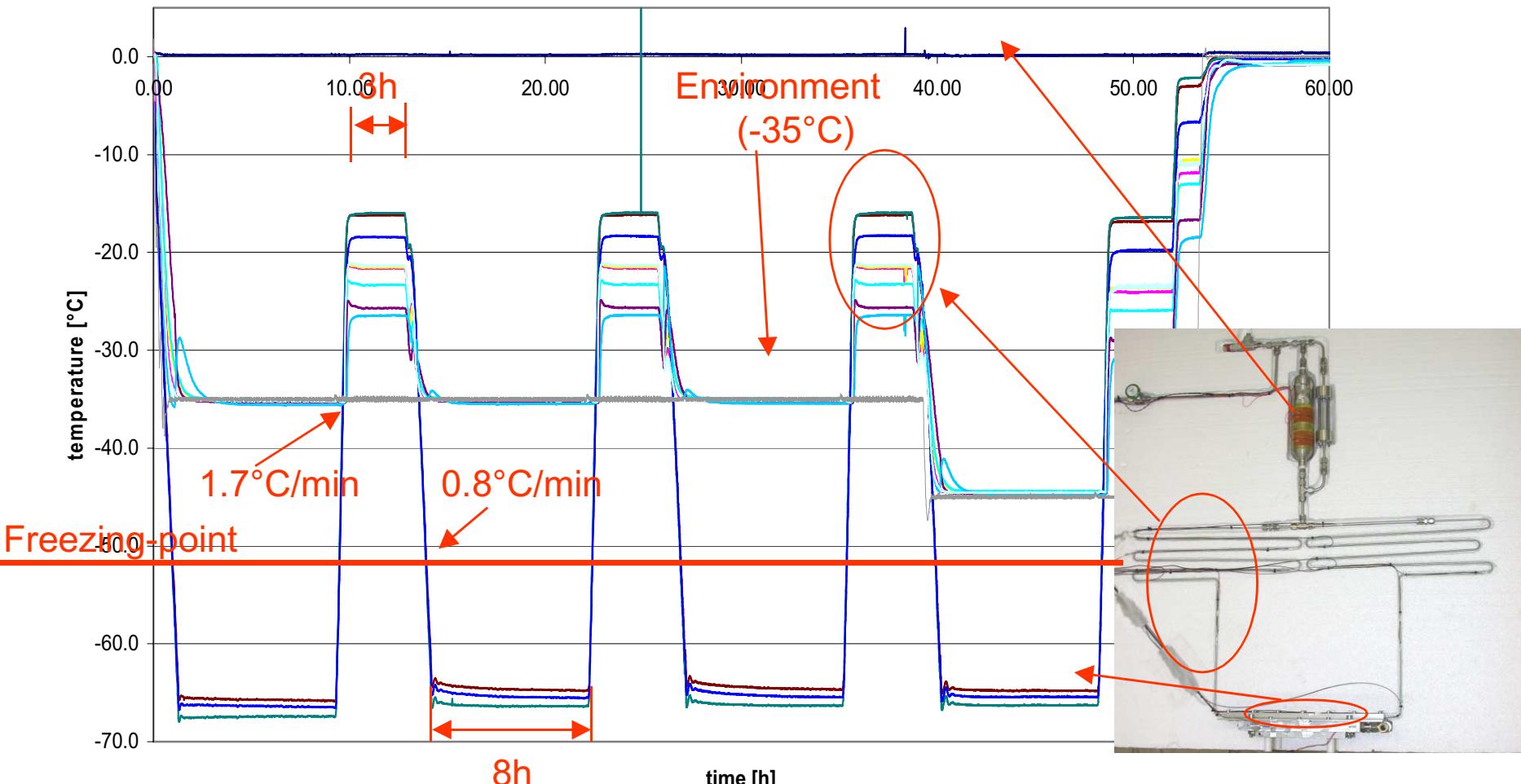
CO₂ freezing test set-up

Tracker T
Temperature Control System

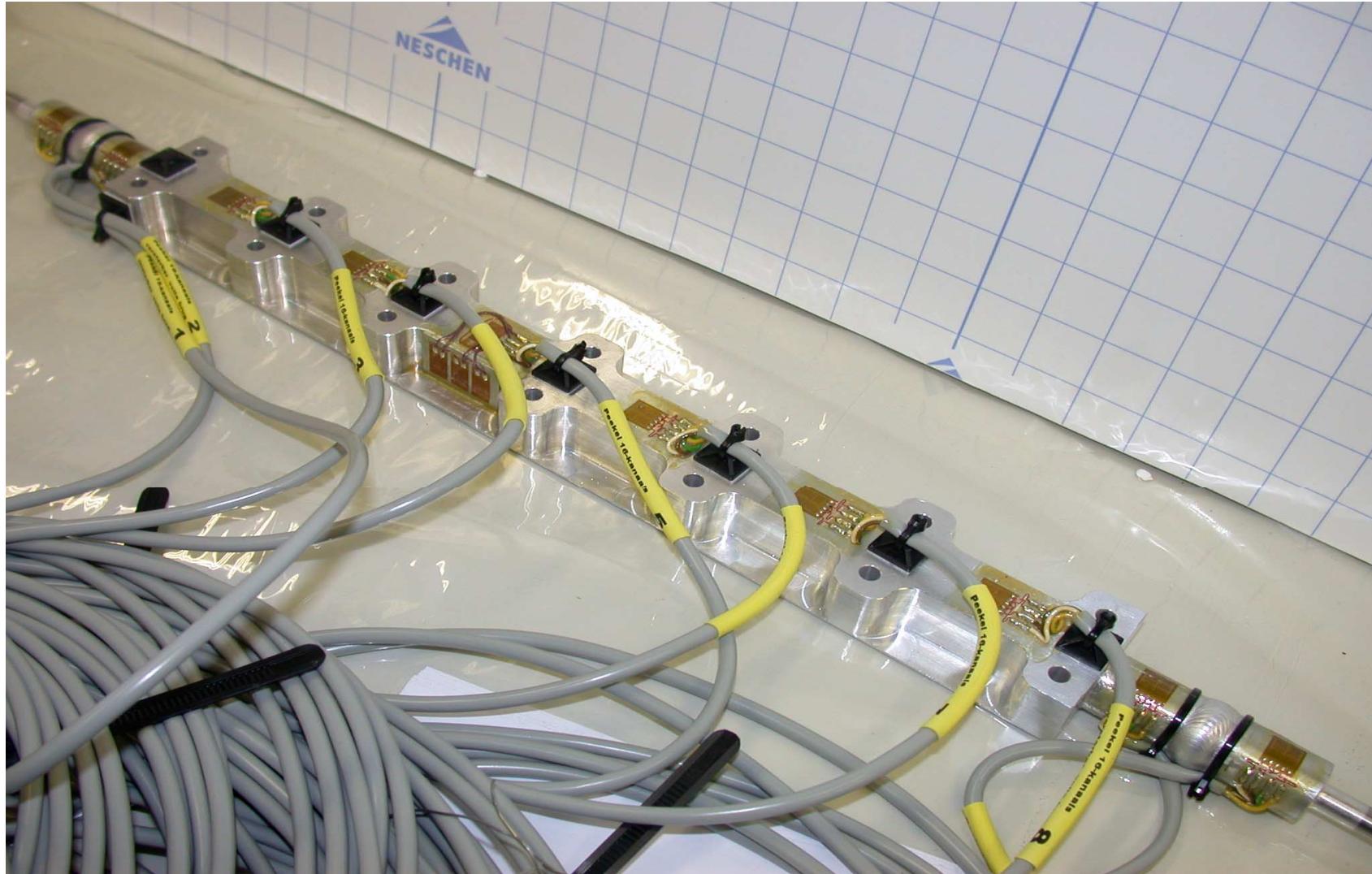


CO₂ freezing test results

Initial tests: limited # thermocouples



Condenser: Freezing test set-up with strain gauges



Conclusions

- No leaks detected during test with tubing.
- All welds are leak tested and proof pressure tested (240 bar)
- Condenser is implemented in test set-up
- Pressure reference tests are performed
- Freezing tests can start soon

Survival heaters in component boxes

- TTCB-boxes are attached to USS-structure

Cold case

- In cold case the lowest truss temperature ($T_{\text{truss}} = 246 \text{ K}$) is above the lower temperature requirement 233 K
- Therefore no or small (< 10 Watt) heaters would be required (TBC for AMS transition from shuttle to truss)

Hot case

- The truss will be used as heat sink for the hot case ($T_{\text{truss}} = 316 \text{ K}$)
- To keep TTCB-boxes box below 80 C pre-heaters should be allocated outside the boxes (allowed ??)
- The additional accumulator heater should be equipped with thermistors (TBC)